LOCATION OF EVENTS IN THE REGION OF BOLIVIA

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ABSTRACT

A fully decoupled nuclear explosion of 10 kT has a magnitude m_b of approximately 3.4. Although a cavity from a previous explosion is needed to fully decouple such an explosion, 3.4 is a useful reference magnitude for the Comprehensive Nuclear-Test-Ban Treaty. There are five principal difficulties in locating events of this magnitude (to ± 18 km) in Bolivia. First, the distance between the primary seismic station in Bolivia, LPAZ, and the auxiliary station, SIV (San Ignacio de Velasco), is approximately 7° and, at this distance, for events of magnitude 3.4, it is easy to misidentify Pg as Pn. The resulting error is approximately 30 s and accurate location is impossible. Second, the Andean crust beneath LPAZ has a thickness of approximately 65 km, whereas the crust beneath SIV has a thickness of approximately 40 km. The higher mantle velocity at a depth of 50 km in the region of SIV moves locations of events in Bolivia toward SIV, unless a three-dimensional location model is used. We have found that for the earthquake near Totora in central Bolivia, 22 May 1998, locations with the three-dimensional program (with grid spacings of 10 km, and then 5 km) are within a carefully studied and closed meizoseismal area. Third, even a three-dimensional model of the Andean region in Bolivia is so different from the reality (and the seismic stations are so widely spaced) that the computed residuals (especially that of depth) indicate only that the location is consistent with the model and the observed arrival times of the P and S phases. At least one S phase is required to control approximately the distance and depth of the hypocenter, but the arrival time of an S phase in Bolivia is usually difficult to observe, because there is rapid subduction of the Nazca plate and volcanism in the west, and a décollement by the Brazil Shield in the east. Fourth, because S is difficult to observe, we do not have much information about S velocities and we use in our three-dimensional models a constant P to S velocity ratio (1.76) for the whole region at all depths; we are correcting this. Finally, international hypocentral determinations in Bolivia have a bias toward the northwest, presumably because the wave paths to central American and North American seismic stations pass once or twice through the higher velocity regions of the Nazca and Cocos subducting plates.

Key Words: Bolivia, earthquake location, subduction.

OBJECTIVES

The objectives of this study were: i) to compare the location of seismic events in the region of Bolivia by horizontally layered models, by three-dimensional models and by international agencies; ii) to check the sensitivity of the primary seismic station in Bolivia (PS 06, LPAZ) of the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) in distance, depth and azimuth with respect to the magnitudes m_b given by the Prototype International Data Centre (PIDC).

TABLE 1. SEISMIC STATIONS OF BOLIVIA OPERATED BY OBSERVATORIO SAN CALIXTO

NAME	CODE	DATE	LATITUDE S	LONGITUDE W	ALTITUDE m	COMPONENT
La Paz, Milluni	LPAZ	1993-....	16°17'16.6" (16°.2879)	68°07'50.4" (68°.1307)	4740	BB-Z-NS-EW; SP-Z
Zongo	BOA	1972 -....	16°16'09.7" (16°.2694)	68°07'26.5" (68°.1240)	4397	SP-Z-NS-EW
Banderani	BOB	1975-....	16°08'39.6" (16°.1443)	68°07'58.4" (68°.1329)	3960	SP-Z
Gloria	BOD	1986 -....	16°38'14.6" (16°.6374)	68°35'53.2" (68°.5981)	4230	SP-Z
Chanca	BOE	1982 -....	16°48'45.7" (16°.8127)	67°58'55.6" (67°.9821)	4325	SP-Z
Collana	BOF	1993 -....	16°57'14.4" (16°.9540)	68°20'16.8" (68°.3380)	4480	SP-Z
San Ignacio de Velasco	SIV	1990 -....	15°59'28.7" (15°.9913)	61°04'19.9" (61°.0722)	520	SP-Z-NS-EW
Mochará	MOCB	1993 -....	21°15'01.5" (21°.2504)	65°38'16.8" (65°.6380)	3580	SP-Z-NS-EW
Warizata	BOG	1999-....	15°56'57.9" (15°.9494)	68°32'43.2" (68°.5453)	4970	SP-Z
Bombeo	BBO	1998-....	17°39'27" (17°.6575)	66°27'27" (66°.4575)	3821	SP-Z-NS-EW
Apacheta	APC	1998-....	17°21'32" (17°.3589)	66°01'30" (66°.0250)	3676	SP-Z-NS-EW
Crr. Ichu Kkollu	IKK	1998-....	17°15'02" (17°.2506)	66°19'32" (66°.3256)	4612	SP-Z-NS-EW
Col. Juan XXIII		1998-....	17°22'30" (17°.3750)	66°11'34" (66°.1928)	2496	CENTRAL STATION

RESEARCH ACCOMPLISHED

A fully decoupled nuclear explosion of 10 kilotons (kT) has a magnitude m_b of approximately 3.4. Nuclear explosions of yields of a few kT with large decoupling factors are feasible only in cavities in salt domes formed by previous nuclear explosions, and no country is known to have evacuated the brine from a very large cavity formed by solution mining and then conducted a decoupled nuclear explosion it it (Sykes, 1996). However, 3.4 is a useful reference magnitude for monitoring the CTBT. A possible on-site inspection area of 1000 km^2 corresponds to an epicenter location accuracy of approximately plus or minus 18 km.

There are five principal difficulties in locating seismic events of this magnitude with this accuracy in Bolivia.

The first difficulty is that the distance between the primary seismic station of the IMS in Bolivia (LPAZ) and the auxiliary seismic station, San Ignacio de Velasco (AS 08, SIV), is approximately 7° (Table 1; Figure 1), and, at this distance, for seismic events of magnitude 3.4, it is easy to misidentify Pg as Pn. The resulting error is approximately 30 s and location to plus or minus 18 km is impossible.

Figure 1. Seismic stations and the proposed infrasound station in Bolivia operated by Observatorio San Calixto.

The seismic stations and the proposed infrasound station in Bolivia operated by Observatorio San Calixto (OSC) are tabulated in Table 1 and shown in Figure 1. We plan to move the short period vertical component of the historically important station Zongo to Warizata (15°.9494 S, 68°.5453 W, 4970 m above sea level), north of the planned infrasound array (IS 08) near Peñas (Figure 1), and the two short period horizontal components to Mochará. The three stations constituting the seismic net around Cochabamba, tabulated in Table 1 (Crr. stands for Cerro and Col. for Colegio) and shown in Figure 1, are at present being calibrated. It is clear from Figure 1 that there are still big spaces between Cochabamba and the seismic stations SIV to the east and Mochará to the south, to say nothing of the space further east and southeast. Location of seismic events of magnitude 3.4 with an accuracy of plus or minus 18 km in this region will be challenging.

Figure 2 shows part of the crustal section of Schmitz (1993; Romanyuk et al., 1999) at 21° S. The seismic station Mochará is a few kilometres north of Tupiza (21°.45 S, 65°.72 W). Distances of the section (km) are measured horizontally from 13 km west of the Chile Trench and vertically from sea level. Curiously, the most interesting figure, the maximum thickness of the Andean crust, 75 km, is uncertain, because Wigger and his coworkers (1994) failed to get a clear Moho reflection east of Ollagüe (21°.23 S, 68°.27 W; 265 km W of Tupiza; Figure 2).

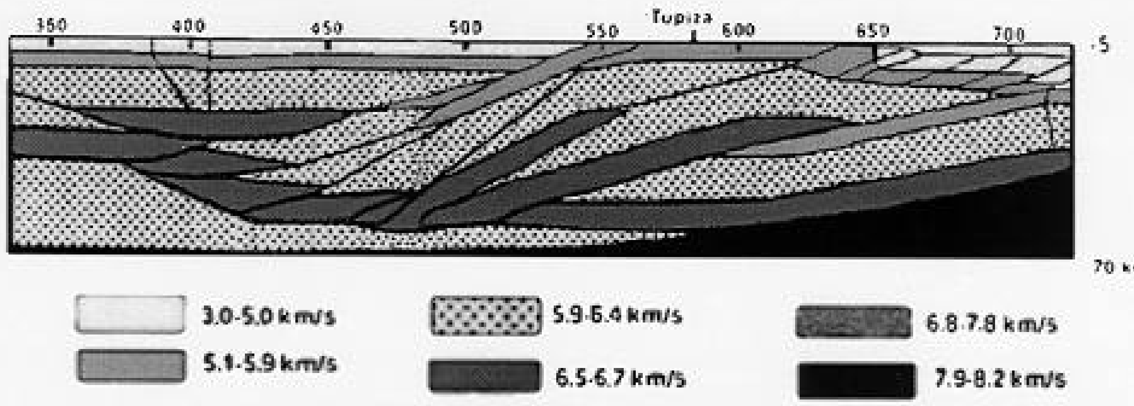

Figure 2. Part of a crustal section (E-W) at approximately 21° S (Schmitz, 1993; Wigger et al., 1994; Romanyuk et al., 1999); distances of the section are measured horizontally from 13 km west of the Chile Trench and vertically from sea level.

Dorbath and her coworkers (1993) estimated a maximum thickness of the Andean crust in the region of La Paz to be 60 km below the Altiplano (cf. Figure 1; 17°.4 S, 68°.4 W). However, these workers note that observed P arrival time residuals from teleseisms are accounted for by depth variations of the sedimentary fill and by variations of the Moho depth: there are basically two unknowns, velocity and depth, and it is difficult to fix the depth of the Moho without detailed knowledge of the velocities in the layers above it. Dorbath and Granet (1996) returned to the problem and found a depth to the Moho under theAltiplano of 66 km; they used the same seismic profile as in 1993, but, in 1996, sources in the Nazca plate subduction zone.

Beck and her coworkers (1994; 1996) used, by receiver function analysis (Ammon et al., 1990), the P to S conversion at the Moho (Ps) and a P that reflects from the free surface and converts to an S wave at the Moho beneath the station (PpPms) to determine the P to S velocity ratio (V_p/V_s). These workers found maximum thicknesses of 70-74 km under the Cordillera Occidental and Cordillera Oriental; these thicknesses thin to 32-38 km, 200 km east of the Andes in the Chaco Plain; the central Altiplano at 20° S has crustal thicknesses of 60 to 65 km. The crust also appears to thicken from north (16° S, 55-60 km) to south (20° S, 70-74 km) along the Cordillera Oriental. However, Beck and her coworkers note that there is a tradeoff between average crustal velocities (V_p and V_s) and crustal thickness, the same problem encountered by Dorbath and her coworkers.

Zandt and his coworkers (1996) used, also by receiver function analysis, an upgoing SV wave that converts to a P wave at the free surface and becomes trapped in the crust owing to its reflection at the Moho beyond its critical angle (sPmP; Langston, 1996); this whole family of P waves can easily be mistaken for S and, at longer period, constitutes a leaky mode (S leaks back into the mantle), similar to the PL phase (Aki and Richards, 1980; p. 460). Zandt and his coworkers (1996) found in the Altiplano a low mean P wave velocity of 6.0 km/s, a low Poisson's ratio of 0.25 and a crustal thickness of 65 km. Again, Zandt and his coworkers encounter the tradeoff problem mentioned above.

Myers and his coworkers (1998) developed a three-dimensional, lithospheric-scale model across the Bolivian Andes at approximately 20° S, based on tomographic images of velocity and attenuation for both P and S waves. Observations of travel time and attenuation for the study of these workers were from regional earthquakes in the mantle and the subducted Nazca plate. The shallow mantle under the Altiplano from approximately 18° S to approximately 21° S has high velocity (approximately V_p = 8.3 km/s, V_s = 4.7 km/s) and moderately high Q (approximately Q_p = 500, Q_s = 200), which suggests lithospheric mantle. High velocity material under the Altiplano extends to a depth of approximately 125-150 km. The shallow mantle of the Cordillera Occidental is characterized by high V_p/V_s (approximately 1.83), which suggests a correlation between V_p/V_s and arc volcanism. Seismic velocities under the Cordillera Occidental are, on average, only slightly reduced from global averages, but velocity and attenuation anomalies are locally strong (approximately V_p =7.8 km/s, V_s = 4.3 km/s, Finally, Chmielowski and his coworkers (1999), again by receiver function analysis, have found, at a depth of approximately 19 km, a very low velocity layer of thickness approximately 0.8 km, with P velocity of approximately 3.5 km/s and S velocity of approximately 0.45 km/s. These velocities correspond to a Poisson's ratio of 0.4916. Thus, this layer almost certainly represents a large sill-like magma body. It has an area of approximately 50,000 km^2, west for approximately 150 km from an approximately north-northwest line joining the points (20° S, 68° W) and (23° S, 67° W); Ollagüe (21°.23 S, 68°.27 W; 265 km west of Tupiza; Figure 2), is near the center of this region. It represents an additional complexity in the crustal structure shown in Figure 2 (Schmitz, 1993; Wigger et al., 1994; Romanyuk et al., 1999).

TABLE 2. CRUSTAL MODEL FOR MOCHARA

Layer thickness km	Compress. velocity km/s	Shear velocity km/s	Density g/cm^3	Poisson's ratio	Quality factor
4.10	5.50	3.19	2.620	0.2474	250
24.30	6.15	3.55	2.724	0.2506	350
9.80	7.30	4.21	2.908	0.2506	450
14.90	6.15	3.55	2.724	0.2506	350
10.80	7.30	4.21	2.908	0.2506	450
63.90	8.05	4.48	3.360	0.2763	600

Table 2 presents a crustal model, based on these observations, for the region of the seismic station Mochará, in the Cordillera Oriental. The layer thickness shown for the half-space below the Moho is the total thickness of the crust of the model (63.90 km, 58.90 km below sea level; cf. the region of Tupiza in Figure 2). The region of the primary seismic station of the IMS of the CTBT, LPAZ, also in the Cordillera Oriental, though further north, can be expected to be over a crustal thickness of approximately 65 km. The seismic station Gloria (Table 1, Figure 1), near the western edge of the Altiplano, can be expected to be over a greater thickness of crust. Values of Poisson's ratio and of Q are taken from the IASPEI (1991) model and from the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981) and values of density are consistent with the Nafe-Drake curve (Grant and West, 1965, p. 200).

TABLE 3. CRUSTAL MODEL FOR REGION OF COCHABAMBA

Layer thickness km	Compress. velocity km/s	Shear velocity km/s	Density g/cm^3	Poisson's ratio	Quality factor
13.10	5.50	3.19	2.620	0.2474	250
14.10	6.15	3.55	2.724	0.2506	350
5.70	5.50	3.19	2.620	0.2474	250
14.70	6.15	3.55	2.724	0.2506	350
8.60	7.30	4.21	2.908	0.2506	450
56.20	8.05	4.48	3.360	0.2763	600

Similarly, Table 3 presents a crustal model for the seismic stations in the region of Cochabamba and Table 4 presents a crustal model for the region of the auxiliary seismic station of the IMS of the CTBT, SIV. Obviously, if horizontally layered models with seismic stations over these different types of crust are used to locate earthquakes in the region of Bolivia, the higher velocities in the mantle at depths of 45-60 km in the region of SIV will bias the location of the events toward SIV.

Table 5 and Figure 3 show, for the earthquake near Totora in central Bolivia, 22 May 1998, the location by the PIDC, the location according to the Preliminary Determination of Epicenters (PDE), the location according to the method of the Harvard central moment tensor (HVD), and locations by Observatorio San Calixto. These latter locations included: i) carefully observed and closed isoseismals, with a depth found by the formula of Kövesligethy (Papazachos and Papaioannou, 1997; Drake and Vega; 1998; Drake et al., 1999); ii) routine location, mainly with the use of French seismic stations in Bolivia and with a model of one horizontal layer over a half-space (Table 6); iii) location with a model of four horizontal layers and the program HYPOCENTER (Table 7; Lienert et al., 1986); iv) location by the three-dimensional program 3DGRIDLOC with a grid spacing of 10 km (Ayala, 1997; Ayala and Drake, 1997; 1998; Podvin and Lecomte, 1991; Tarantola and Valette, 1982; Vidale, 1988; 1990; Wittlinger et al., 1993) ; v) location by the three-dimensional program 3DGRIDLOC with a grid spacing of 5 km.

TABLE 4. CRUSTAL MODEL FOR SAN IGNACIO DE VELASCO

Layer thickness km	Compress. velocity km/s	Shear velocity km/s	Density g/cm^3	Poisson's ratio	Quality factor
9.73	4.00	2.32	2.380	0.2474	180
5.26	5.50	3.19	2.620	0.2474	250
15.34	6.15	3.55	2.724	0.2506	350
9.67	7.30	4.21	2.908	0.2506	450
40.00	8.05	4.48	3.340	0.2763	600

TABLE 5. LOCATIONS OF AN EARTHQUAKE BY THE PROTOTYPE INTERNATIONAL DATA CENTER, ACCORDING TO THE PRELIMINARY DETERMINATION OF EPICENTERS, ACCORDING TO THE HARVARD CENTRAL MOMENT TENSOR METHOD AND BY OBSERVATORIO SAN CALIXTO

Source	Time h m s	Latitude °S	Longitude °W	Depth km
PIDC	04 48 48.2	17.54	65.14	34
PDE	04 48 50.4	17.731	65.431	24
Harvard CMT	04 49 02.9	17.600	65.070	15
3DGRIDLOC	04 48 46.2	17.810	65.100	1
3DGRIDLOC, 5km	04 48 45.2	17.920	65.180	1
OSC, French	04 48 44.8	17.883	65.050	9
OSC, Lienert	04 48 43.6	17.804	65.057	13
Isoseismals		17.850	65.160	11

TABLE 6. LAYER OVER HALF-SPACE MODEL FOR CENTRAL BOLIVIA

Layer thickness km	Compress. velocity km/s	Shear velocity km/s	Poisson's ratio
65.0	6.2	3.580	0.25
	8.0	4.619	0.25

TABLE 7. FOUR LAYER MODEL FOR CENTRAL BOLIVIA

Layer thickness km	Compress. velocity km/s	Shear velocity km/s	Poisson's ratio
10.0	5.0	2.8090	0.2694
15.0	6.0	3.3708	0.2694
35.0	6.6	3.7079	0.2694
120.0	8.0	4.4944	0.2694

The locations the by the PIDC and according to the method of the Harvard central moment tensor (HVD) appear to be approximately 35 km too far north, and the location according to the PDE appears to be about 30 km too far northwest. As expected, the locations with the horizontally layered models are pulled toward SIV. The locations by the three-dimensional program 3DGRIDLOC are within the meizoseismal area.

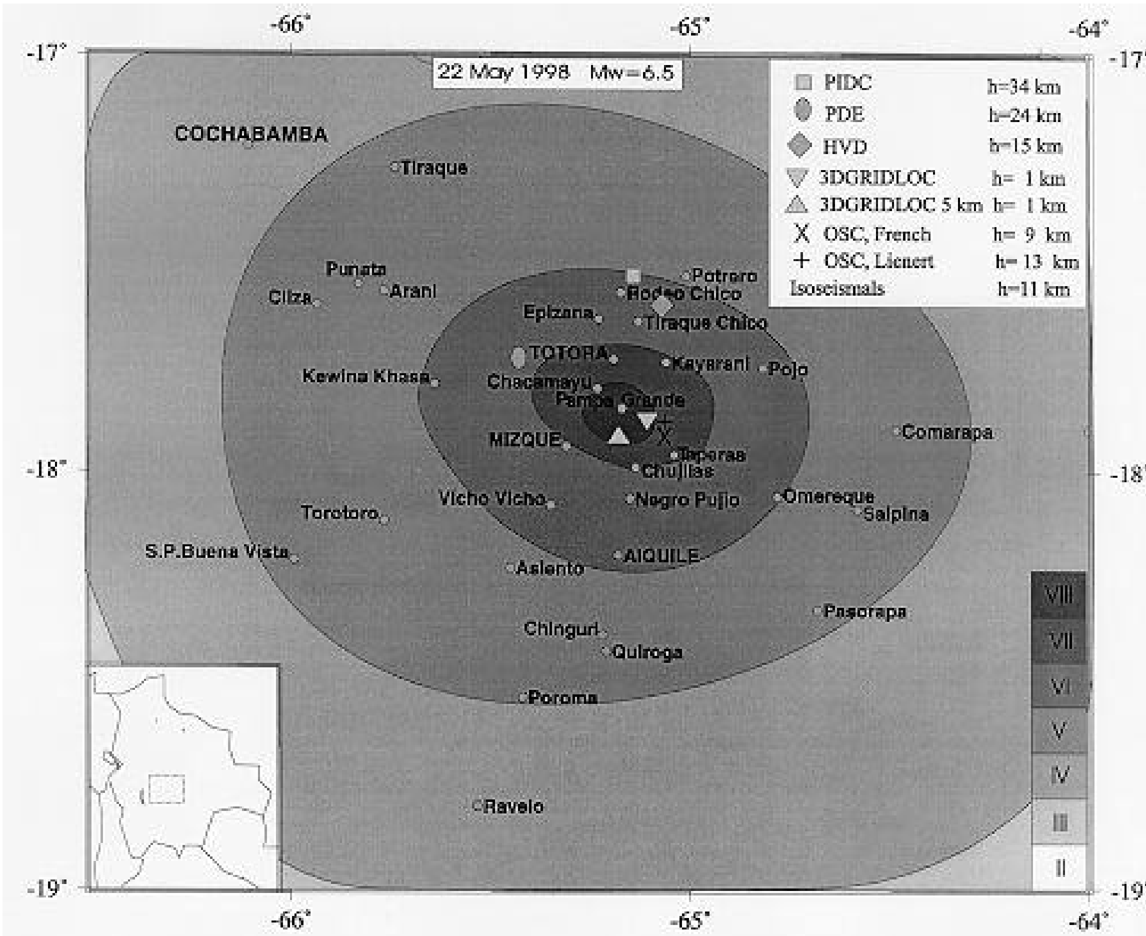

Figure 3. Isoseismals for the earthquake of 22 May 1998 near Totora in central Bolivia, together with locations by the PIDC, by the PDE, by the Harvard central moment tensor method (HVD) and by Observatorio San Calixto.

The third principal difficulty with the accurate location of earthquakes in Bolivia is that even a three-dimensional model of the region is so different from the actual structure of the earth beneath the Bolivian Andes and the seismic stations are so widely spaced that the computed residuals (especially that of depth) indicate only that the location is consistent with the model and the observed arrival times of the P and S phases. At least one S phase is required to control approximately the distance of the hypocenter from the seismic stations (especially its depth). However, the arrival time of an S phase in Bolivia is usually difficult to observe, because there is rapid subduction of the Nazca plate and volcanism in the west (Gordon, 1995; Norabuena et al., 1998; Kendrick et al., 1999), and a décollement by the Brazil Shield in the east (Sempere et al., 1988; Gubbels et al., 1993; Jacobshagen et al., 1998; Lamb and Hoke, 1997; Lamb et al., 1997). The S phase from the approximately north-south bands of deep earthquakes in Peru-Brazil (6°.5 S, 71°.5 W to 11°.5 S, 70°.8 W) and in Bolivia-Argentina (19°.0 S, 63°.5 W to 28°.5 S, 63°.0 W), and also from the region of Totora (17°.60 S, 65°.15 W) in Bolivia, is comparatively clear. However, S from southern Peru (e.g. Arequipa, 16°.40 S, 71°.55 W) and Chile is likely to be confused with the more conspicuous R_g. Also, in the region of Bolivia, PpPms (Beck et al., 1996), sPmP (Zandt et al., 1996) or a trapped low velocity phase (Chmielowski et al., 1999) can be mistaken for S.

The fourth principal difficulty with the accurate location of earthquakes in Bolivia is that, because S is difficult to observe, we do not have much information about S velocities. Our three-dimensional models of the region used in the programs 3DGRIDLOC use a constant V_p/V_s ratio of 1.76 for the whole region at all depths, which is not realistic. We are correcting this.

Finally, the fifth principal difficulty with the accurate location of earthquakes in Bolivia is that international hypocentral determinations in Bolivia have a bias toward the northwest. This occurs possibly because the wave paths to central American and North American seismic stations pass once or twice through the higher velocity regions of the Nazca and Cocos subducting plates. Under central America at a depth of 150 km there appears to be a low S velocity region, but at a depth of 550 km the S velocity is more normal (Dziewonski, 1989). Because errors of location of earthquakes by the PIDC clearly depend on which seismic stations are used, the practices of kriging (interpolation of location corrections relative to reference "ground truth" events; Schultz et al., 1998) and of plotting error vectors of arrays or stations relative to supposed "correct" locations of the PIDC (Koch and Kradolfer, 1999) are no substitute for close azimuthal cover in the accurate location of earthquakes (Lienert et al., 1986).

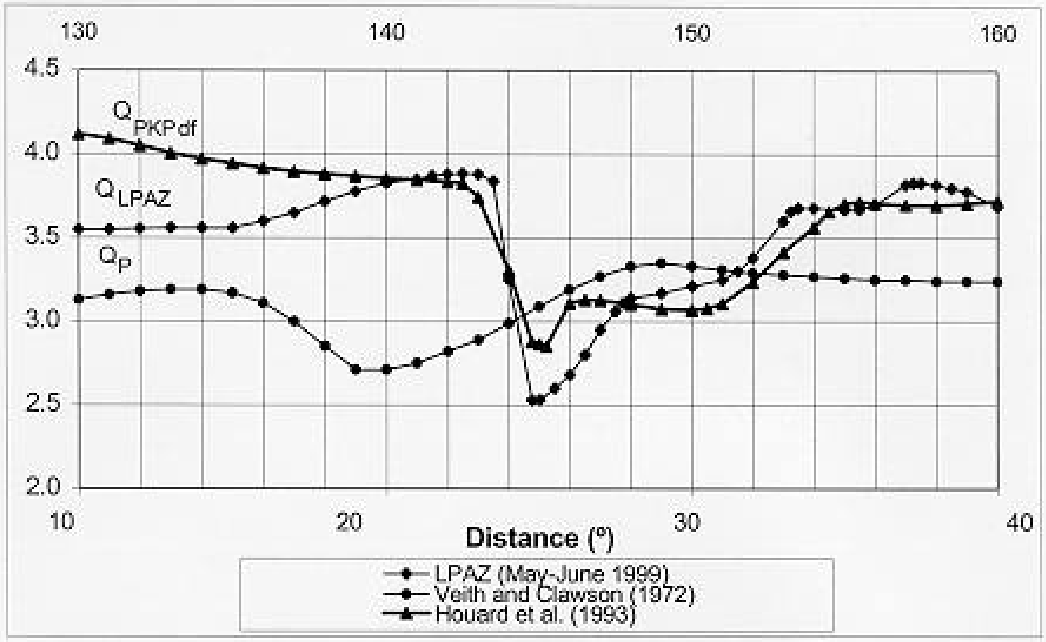

Figure 4. Q for the IMS primary seismic station LPAZ from 130° to 160° for May and June 1999 compared with Q for PKP_{df} and PKP_{bc} (Houard et al., 1993) and with Q for P from 10° to 40° (Veith and Clawson, 1972).

The promptness of the PIDC preliminary locations has now enabled seismologists to obtain locations of earthquakes before they see seismograms. Figure 4 shows the sensitivity (approximate Q) of the IMS primary seismic station LPAZ between distances of 130° and 160° compared with the Q values derived for the phases PKP_{df} and PKP_{bc} for the model 1066B (Gilbert and Dziewonski, 1975; Houard et al., 1993) and the Q values of Veith and Clawson (1972) for events between distances of 10° and 40° (at a depth of 15 km). The approximate LPAZ values are derived from amplitudes observed in May and June of 1999, without distinction of period, depth or azimuth; the apparently low Q between distances of 130° and 140° appears to be from the phase PKhKP. The apparently sharp decrease in Q shown for the phase PKP_{df} between distances of 142°.8 and 154°.8 is from the phase PKP_{bc} (Houard et al., 1993). The IMS seismic station LPAZ appears to be more sensitive to events between distances of 144° and 151° than to events between distances of 10° and 16°.

CONCLUSIONS AND FUTURE PLANS

Location of seismic events in Bolivia to plus or minus 18 km, with control of depth, needs close azimuthal cover of seismic stations, an appropriate earth model and observation of at least one S phase. At present the three-dimensional models 3DGRIDLOC do not include appropriate S values and we need to correct these. S is usually difficult to observe in Bolivia and we need to examine methods of detecting it. Finally, we can look more at the effect of period, depth and azimuth on amplitudes of phases observed at the IMS primary seismic station LPAZ of the CTBT.

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